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Dynamical studies on laser processes induced by short pulse lasers: from nanoseconds to milliseconds

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- Invited Paper -

Abstract

Laser processes induced by short pulse lasers are widely applied in industries and research fields. Details of these processes depend on the laser wavelength and pulse duration of lasers used, materials irradiated, irradiation conditions such like power density and repetition rate and other parameters. To elucidate the details of these processes, we have developed a technique, which is named as high-speed laser stroboscopic videography, to take fast videos to visualize these processes. By combining a newly developed high-speed video cameras and high-repetition rate short pulse lasers, the technique allows us to take videos as fast as 1 μ s interval in several recording modes, and gives unique information on several laser processes. In this paper we presents some examples of such studies on laser peening, dynamics of laser-induced bubbles in liquids, and micromachining on hard and brittle materials by a femtosecond laser.

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1. Introduction

Short-pulse lasers are widely used in laser-induced processes in various practical applications and scientific researches. Short pulse-laser processes start by interactions of laser radiation with materials, by which the laser pulse

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energy is transferred to the material to induce some changes in it. This initial process occurs in very short time, approximately equals to the laser pulse durations, and require sophisticated high-speed equipment to visualize them. The initial process is followed by other slower processes such like phase changes of the material, interactions with surrounding atmospheres, movement and shape change of the matter and thermal and mechanical effects. These changes occur both in time and space and it is essential to observe not only the time variations of physical parameters at a fixed point but also the spatial changes of the process in time.

Therefore we have developed a custom-designed high-speed videography system designated “high-speed laser stroboscopic videography (HLSLV)” to observe such laser-induced processes in wide time scales from microseconds to seconds with a moderate spatial resolution. Tanabe et.al., (2005). Using this system, we are able to acquire images continuously at intervals as short as 1 μ s and at a high time resolution of less than 0.1 ns. The technique is a combination of a high-speed video camera with a high-repetition rate, short pulse laser and its recording speed depends on the repetition rates of the camera and the laser. At present, both repetition rates are 1 MHz at the highest and observations on events occur faster than 1 μ s require other methods, such like high-speed pump-probe photography technique, a framing streak camera or sequentially timed all-optical mapping photography (STAMP), which is recently developed by Nakagawa et. al. (2014) and Suzuki et al. (2015). These techniques, however, require very sophisticated equipment and techniques and can capture only a limited number of images, one or a few frames, for single event and a large number of measurements must be repeatedly performed to observe whole event which might extends from femto- and pico-seconds to milliseconds. Such repeated measurements are time-consuming and subject to shot-to-shot fluctuations of the event. Our HLSLV technique can record continuous images for a single event and is a complementary technique to the other high-speed imaging techniques mentioned above. Here we present three examples from our dynamic observations on laser-induced processes, laser peening, dynamics of laser-induced bubbles in liquids by a nanosecond laser and micromachining on hard and brittle material by a femtosecond laser.

2. High-speed laser stroboscopic videography (HLSLV)

2.1. Basic system

Our high-speed videography system was initially developed for dynamical observation on rapid shaping of a thin needle in single discharge phenomena using a thin electrode. A thin needle of less than 10 μ m in diameter was instantaneously formed on the tip of tungsten electrode of 100 μ m diameter by single discharge of a few hundreds microsecond duration. Tanabe et al. (2005, 2009, 2011) and Ito et al. (2007). During the discharge, strong emission from arc plasma makes it difficult to observe the electrode shape change and a high-speed video camera takes only emission image of the plasma. We used a short pulse laser at 532 nm as a back-light source of the video and placed a band-pass filter at 532 nm in front of the camera to allow only the laser light reach the camera. By this combination, we could completely suppress the plasma emission and observe the shape change of the electrode during and after the discharge. Obtained videos indicated that the thin needle was the center part of the electrode left unmelted during the discharge and appeared as surrounding melted part moved upward due to surface tension of the melt. Ito, et al. (2007) and Tanabe et al. (2009).

This technique has other merits: (1) Effective shutter speed is determined by an illuminating laser duration just like a stroboscope and it is much shorter than shutter speed of the video camera, (2) Laser pulse energy of approximately 1 μ J or less is bright enough to give clear images in shadowgraph mode and need not to use high-power light sources, (3) It is easy to construct several types of imaging optics due to the high directivity of the laser beam, even though the high coherency of the laser might cause some interference effects in captured images, (4) The single laser beam can divide into two or more optical paths to take multiple videos simultaneously if we have two or more cameras while timing of each frame recorded in different videos is exactly synchronized because the each illuminating laser pulse is originated from single pulse.

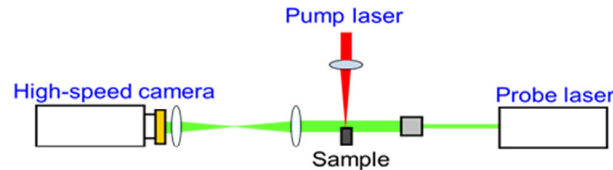


Fig. 1. Principle of high-speed laser stroboscopic videography (HSLSV) system. A digital delay generator synchronizes the camera and the probe laser pulse and the pump laser triggers recording of video.

2.2. System construction

In this paper, we present two types of HSLSV systems consisted from combinations of different video cameras and lasers. One system employs a high-speed video camera, which can operate as fast as 1 MHz with 312 x 260 pixels image but can acquire only 102 frames (Shimadzu Hyper Vision HPV-2A). Etoh, et.al. (2003), Thoreddesen et.al., (2006). A laser used as a light source can operate at high repetition rate of up to 1 MHz at 532 nm and 35 ps pulse duration (Fianium HE532). Another system uses a video camera which can operate at 50 kHz with 384 x 256 pixels image but takes 4000 or more continuous images (Photron Fastcam SA 1.1). The basic system design is illustrated in figure 1.

In some experiments, a nanosecond laser at 532 nm is also used as an illuminating laser source. The first system is mainly used in high-speed observation of the single event while the second used in observations for longer time scale and for a multiple irradiation event. Laser beams are expanded to illuminate areas about 10 x 10 mm² and neutral density filters and beam attenuators adjust their intensity. Images are magnified by combination of simple lenses to appropriate scale and projected on to the cameras through a band-pass filter at 532 nm. Other optical components, such as waveplates, polarizers or a knife-edge are placed in optical path when needed.

3. Dynamical visualizations through high-speed laser stroboscopic videography

3.1. Laser peening

Technologies of laser peening have been applied in industry to improve toughens and hardness of materials, especially of metal surfaces. In many cases, laser peening is carried out with some sacrificial layers or under liquids to obtain higher stress and protect the peened surface from direct laser irradiation. Laser peening under liquids is effective due to so-called confinement effect of the liquid layer on laser-induced plasma. It is rather difficult to measure the magnitude of laser induced stress directly and the effects have been estimated from hardening of the material after the peening with comparison to the numerical simulations. We have been applied our video systems to observe the laser peening process under liquid to visualize the confinement effects and the role of the liquid layer.

To visualize the laser-induced stress, we have constructed a circular polariscope system with epoxy-resin block targets. The laser induced stress field was visualized as a photoelastic image while the stress wave and plasma/bubble dynamics in liquids was recorded as shadowgraphs. Earlier phase of the peening process was visualized by a conventional pump-probe high-speed photography because we employed a nanosecond laser as a pump laser and required faster observation than one microsecond. Figure 2 shows examples of images obtained by the pump-probe photography and figure 3 shows those obtained by the HSLSV. The propagation of shock waves and expanding and collapsing processes of cavitation bubbles on a solid surface were observed in liquid, together with the simultaneous observation of the development of stress fringes in the solid sample. Nguyen et al. (2013, 2013, 2014). It was verified that number of photoelastic fringes was a measure of the magnitude of stress inside the solid. The videos clearly showed that the secondary stress field and shock waves were generated when the first cavitation bubble collapsed and its magnitudes were approximately 30 % of the first stresses induced when the first bubble was generated. Effects of water layer thickness on laser-induced stress were visualized and estimated. Tanabe et al. (2014).

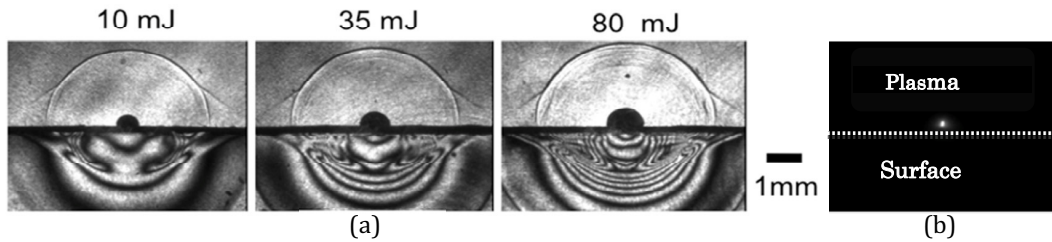


Fig. 2. Examples of photoelastic images obtained in water at 1500 ns after irradiation of (a) 10, (b) 35, (c) 80 mJ pulses focused on to the sample surface and (d) plasma emission recorded for 80 mJ pulse at 50 ns after irradiation. Figures (a) to (c) clearly show shock waves propagating into water and photoelastic fringes propagating into epoxy resin blocks. Small black semi-spheres at the center are laser-induced cavitation bubbles. Number of fringes and the size of the bubble increase with increasing pulse energy while the size of shock front in water only slightly increases. Nguyen et al. (2013, 2013).

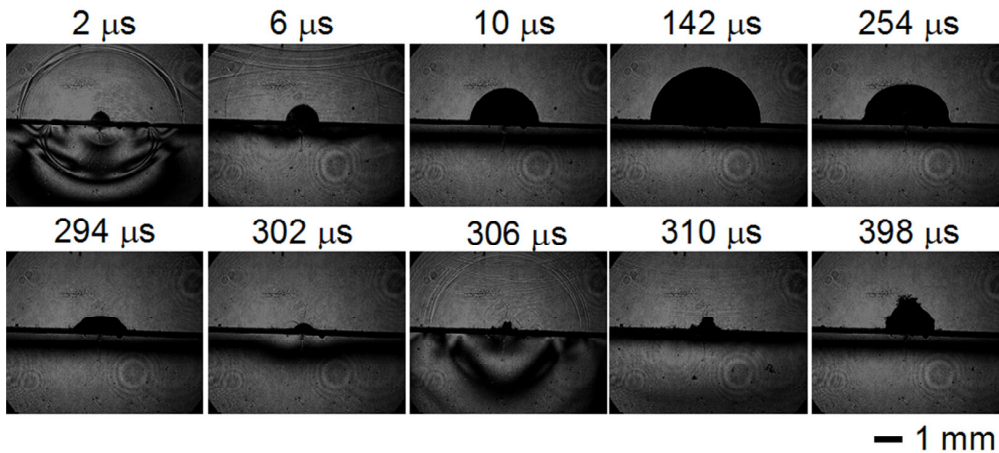


Fig. 3. Dynamics of laser induced bubble and stress field in epoxy resin block under water for 60 mJ laser pulse. Nguyen et al. (2014).

3.2. Dynamics of laser-induced cavitation bubble

Results shown in the previous section suggests that our HSLSV system is suitable for studies on dynamics of laser induced cavitation bubbles in liquids. Cavitation bubble dynamics in liquids have been studied in fluid mechanics as well as mechanical importance of cavitation erosion. Vogel and Lauterborn (1988), Sasoh et al. (2005), Lauterborn and Vogel (2013). Figure 4 are picked up images from a video to show the time evolution of a cavitation bubble induced in water from a 100-mJ laser pulse focused into 10 mm below the water surface. The images obtained from our system were much sharper than those of previous shadowgraph reports by Petkovšek and Gregorčič (2007) because very short light pulses with durations of only 35 ps projected our images, which is much faster than the speed of bubble expansion. In addition, these images are captured for single event and free from shot-to-shot variations of events. Top row represents the first bubble dynamics while bottom row the second, rebound bubble dynamics. The first bubble keeps rather well-defined spherical shape during its expansion and shrinkage with its center at fixed location, as indicated by a dotted line in the figure. The center position starts to move downward in 462 μ s image and during its collation phase, the center position further moved downward, as shown in the bottom row. Then the center of the second bubble remained at approximately the same location until the second collapse. Shape of the second bubble becomes deformed and irregular. Emission of shockwaves is clearly observed in images

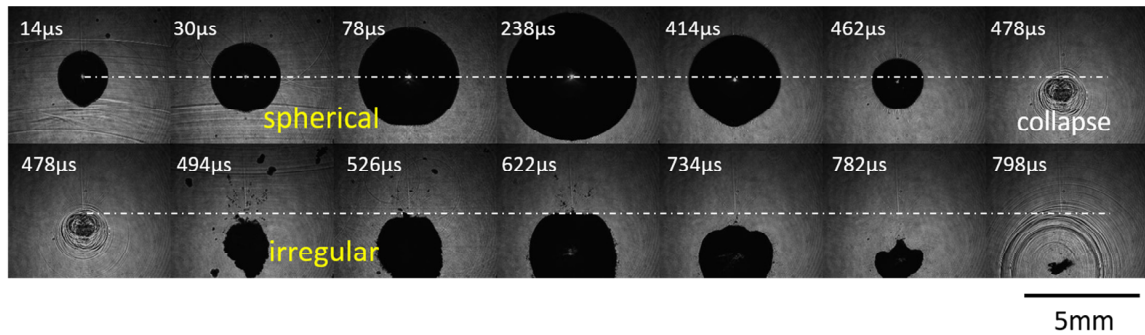


Fig. 4. Picked-up images from a video to show the time evolution of a cavitation bubble induced in water for a 100-mJ ablation laser pulse. Top row represents the first bubble dynamics and bottom row the second, rebound bubble dynamics. The image at 478 μ s is shown in both rows for comparisons sake.

at 487 μ s and 798 μ s, when the first and the second bubble collapse. Effects of liquid viscosity on the bubble dynamics have rarely been studied so far. Numerical simulation study has reported that effects of the viscosity are rather small, but we do not find any experimental study on this issue. We used silicon oils with wide range of kinetic viscosities. Viscosity, density and refractive index of water and silicon oils used are listed in table 1. Silicon oils have approximately the same density and refractive index and have similar chemical composition and structure, poly-(di-methyl silicone), except for molecular weight and viscosity. We can expect that if there were some changes in the bubble dynamics, it would be the effects of viscosity.

The lifetime of the first bubble was found to be dependent on the maximum size, and was therefore longer for larger pulse energies as shown in figure 5. The maximum bubble diameter decreases with increase in the kinetic viscosity of the liquid. The initial growth and final shrinkage of the bubble were observed to occur very quickly,

Table 1. Physical properties of water and silicon oil.

Media	Viscosity / cSt	Density / kg m ⁻³	Refractive index
Pure water	0.893	997	1.333
	10	933	1.399
	100	963	1.403
Silicon Oil	1,000	968	1.403
	10,000	973	1.403
	100,000	975	1.403

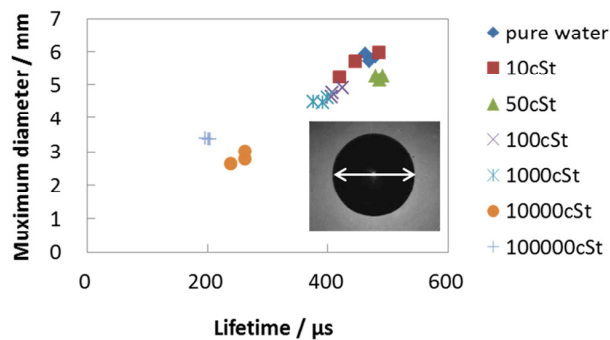


Fig. 5. The maximum diameter and the lifetime of the first laser cavitation bubbles in water and silicon oils with 10 to 100,000 cSt. The maximum bubble diameter decreases with increase in the kinetic viscosity of the liquid. Their correlation is fairly good and thus the viscosity has little effects to the bubble dynamics.

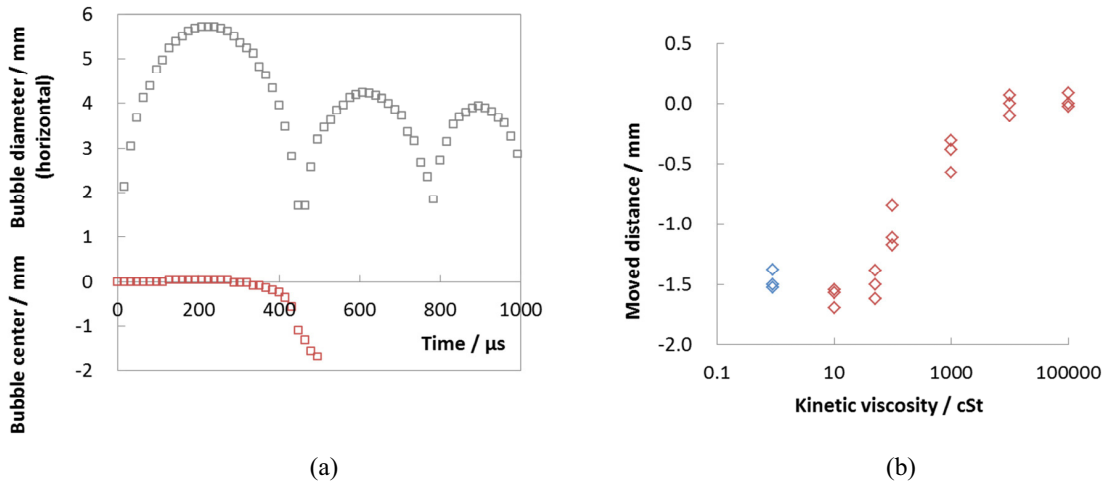


Fig. 6. (a) Cavitation bubble diameter measured in horizontal direction and its center location for induced in 10 cSt silicon oil from a 100-mJ ablation laser pulse as a function of time after irradiation. Center location moved downward when the first bubble collapsed and the distance of this movement is varied with viscosity of the media, as shown in (b).

with speeds exceeding 50 ms^{-1} . Therefore, observations at the shortest interval of $1 \mu\text{s}$ were carried out to examine the phenomena in detail during these periods. The results summarized in figure 6 clearly showed that displacement distance decreased with kinetic viscosity, suggesting that this phenomenon was driven by liquid flow around the bubble. This sequence repeated several times for lower viscosity liquids with formation of more irregular shaped and smaller bubbles while only occurred a few times for higher viscosity liquids. In the highest viscosity of 100,000 cSt, the first bubble did not completely collapse and formed a permanent bubble suspended in the liquid. We consider that the silicon oil might polymerize due to the heat of laser-generated plasma and formed a balloon-like bubble.

3.3 Micromachining on hard and brittle materials by a femtosecond laser

Machining characteristics of materials by pulse lasers strongly depends on number of pulses irradiated on the same position. To understand the machining process clearly, it is important to observe how machining dynamics

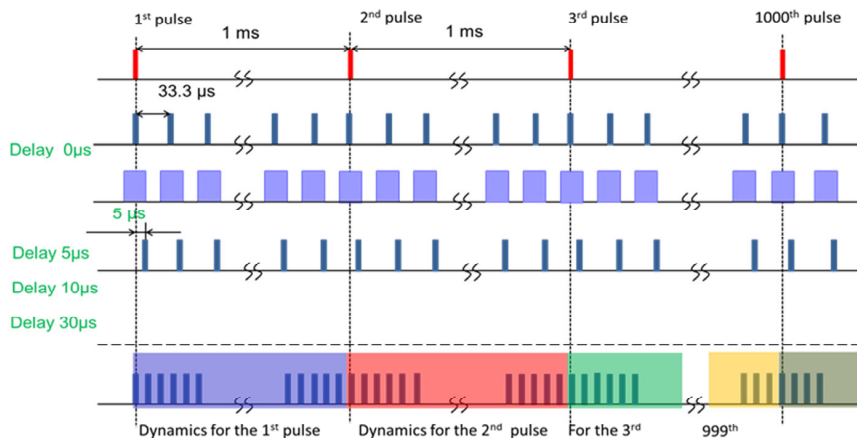


Fig. 7. Timing chart of the video frame, the illuminating laser pulse and the femtosecond laser pulses. Delay 0 indicates that the femtosecond laser pulse synchronizes to the probe laser and camera gate, while delay $5 \mu\text{s}$ etc. indicate designated delay is given to the probe and camera gate.

depends on the number of irradiated pulses. We have modified the HSLSV system to allow us to visualize machining dynamics of each pulse in continuous multiple pulse irradiations. The system was based on the second system described in the section 2.1. An ultrafast, femtosecond laser was used in percussion drilling of hard materials, cemented tungsten carbide (WC). The camera and the visible laser were operated synchronously at 30 kHz or 50 kHz and the ultrafast laser was operated at 1 kHz. The resolution of each frame of the camera was 384 x 256 at 50 kHz. Thus 30 images with 33.3 μ s interval or 50 images with 20 μ s interval were recorded for each laser shot. Timing chart of these events is shown in figure 7.

This system was further modified to obtain faster, shorter interval observations by taking a series of videos with designated delay between the pump pulse and the probe and the camera gate as indicated in the figure. For example, if we set the delay in 5 μ s increment and take 6 series of videos, we can reconstruct a 5 μ s interval video, even though the video is not recorded for single event.

In case of pulse laser processing, pulse duration, repetition rate and pulse overlap have also great influence in processing results. These parameters frequently influence each other and thus our understandings of laser processing become difficult. In many cases, therefore, the effects of a set of parameters are compared with other sets on the bases of obtained results observed after the process and thus the role of these parameters are not clear. Most studies on dynamics of laser ablation in machining, including our own studies, have investigated on single pulse dynamics and the change of dynamics due to multiple pulses has not been studied in detail. Many laser ablation processes, however, require multiple pulse irradiations on single point from 10 to 10^3 pulses or more. In these circumstances, each laser pulse interacts with material under different conditions because they would change with preceding pulses. Ablation dynamics would also change with number of irradiated pulses. Our purpose is to observe the change of ablation dynamics with number of irradiated pulses.

Figure 8(a) illustrates optical arrangement for observation of percussion drilling on cemented tungsten carbide (WC) sample. Diameter of drilled hole increased rapidly in initial ten to twenty pulses, reached a plateau until 100 pulses, and then gradually increased again. Effects of the laser pulse energy, focus position and polarization have been studied. It is rather difficult to comprehend the changes in the process from still images picked up from the video, even though we could comprehend some changes in viewing the video. So we tried to construct subtraction (differential) images in which only the change occurred in two images was enhanced and extracted. Two subsequent images are picked up from the video and a differential image of the two was made. Figure 9 shows examples of differentiated (subtracted) images at -33 to 105 μ s after the 100th pulse in top row and images at 5 μ s after 1st to 700th pulses in bottom row. In 0 μ s image, emission of ablation plasma is observed as a white spot and white circular area appears in images at 5 μ s and later. We think this white area corresponds to deposition area of ejected debris from the drilled hole. At 100th pulse, this area can be observed until around 200 μ s. This suggests that deposition of

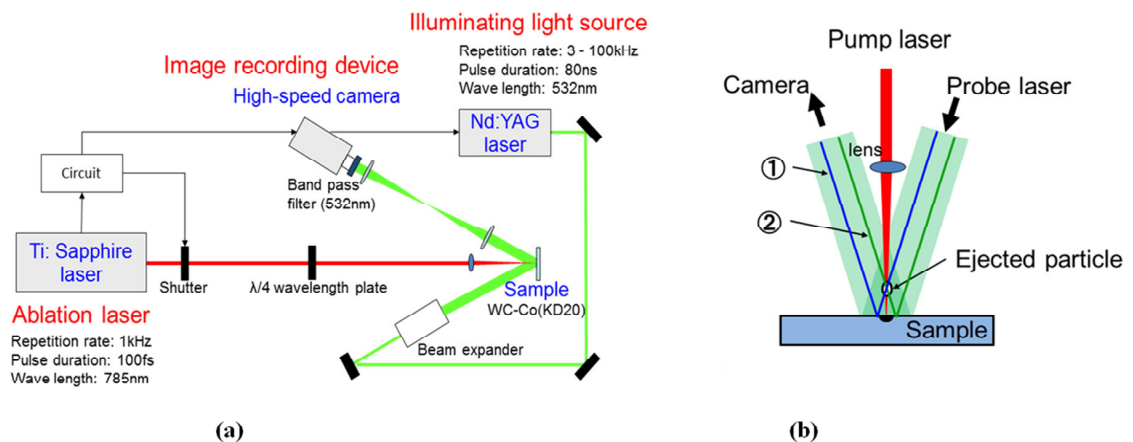


Fig. 8. (a) Schematics of the optical arrangement of HSLSV system for observing percussion drilling process on WC and (b) geometrical illustration in interpretations for observed images.

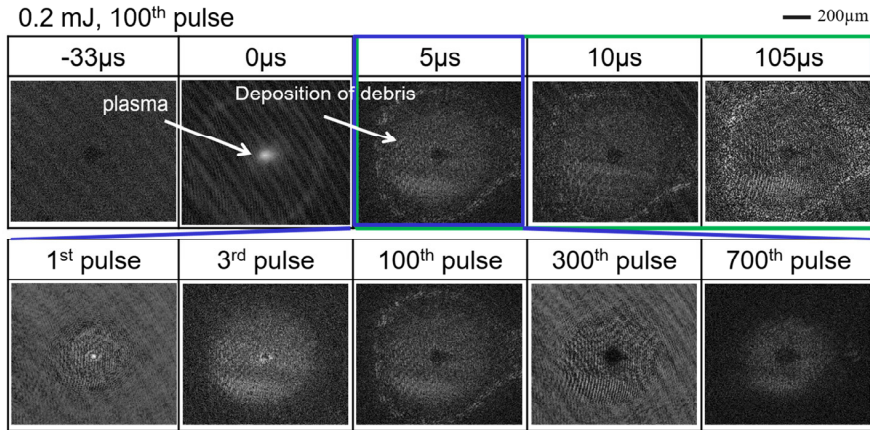


Fig. 9. Examples of images after subtraction at -33 to 105 μ s after the 100th pulse (top row) and images at 5 μ s after 1st to 700th pulses (bottom row).

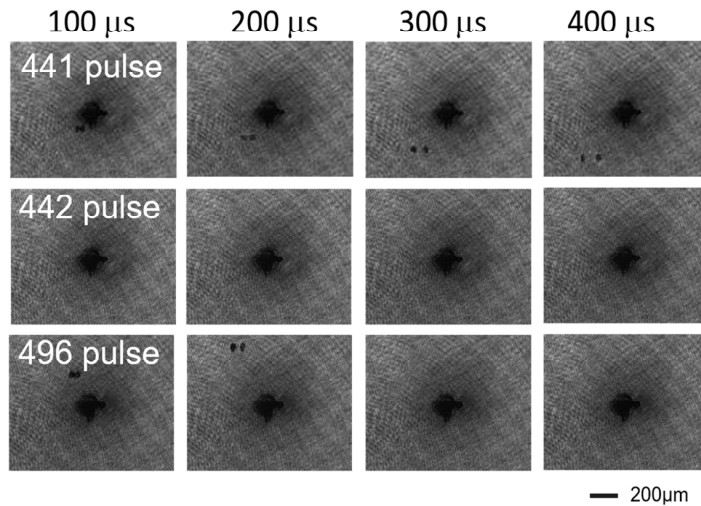


Fig. 10. Ejection of particulate debris occurred from 441st and 496th pulse but not from 442nd pulse. Black round circle at the center is drilled hole and ejected debris appears as pair of black dots in the image because one particle intersects two different position of the illuminating laser beam as illustrated in figure 8 (b). The pair changes their position in time. Dots located in horizontal direction in the image correspond to the direction of laser illumination. Simple trigonometry allows us to estimate the height of the debris and location as a function of time and thus we could estimate the ejected speed of the debris.

fine debris continues until this timescale. This area becomes smaller when the irradiated pulse number exceeds 100 to 200 pulses and is nearly halved at 700th pulses as shown in bottom row of the figure. This debris should be very fine particles for we could not see clear shadow of them.

Large size debris was ejected only occasionally. Thus the most of the removed materials should be ejected in gas or very fine, less than micrometre-sized, particles. Figure 10 shows such images; at 441st pulse pair of black spot and moved downward with increasing separation and at 496th pulse and similar pair moved upward in the image, but we could not observe such dots at other pulses, e. g., at 442nd pulse shown in the middle row. These pair of dots is shadows of one ejected particle as ejected debris appear as pair of black dots in the image; one particle intersects

two different position of the illuminating laser beam as illustrated in figure 8 (b). Simple trigonometry allows us to estimate the height of the debris and location as a function of time and thus we could estimate the ejected speed of

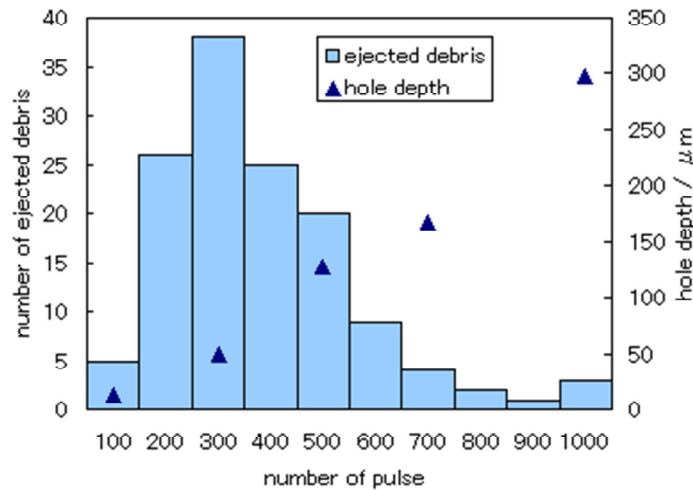


Fig. 11. Frequency of particle ejection from the drilled hole as a function of irradiated number of pulses for percussion drilling on cemented WC in air. The drilled hole depth is also plotted in the figure.

the debris, approximately 1 m/s in average but varies from particle to particle. The size of particulate debris also varies but their average size is estimated to be approximately 30 μm . In some cases, two or more particles were ejected for one laser pulse and figure 11 shows statistic results of the particle ejection as a function of irradiated pulse number. The hole depth measured after irradiation is also plotted in the figure. Ejection of particles occurs most frequently at irradiated pulse numbers around 300, where the hole depth is approximately 50 μm . The number of ejected particles gradually decreases with increasing pulse number and becomes quite rare for 700 or more pulses, where the hole depth exceeds 100 μm .

Deposition area of fine debris around the opening of the hole decreases for larger number of pulse as shown in figure 9. We consider that ablated materials would deposit inside of the drilled hole at larger number of pulses and large particulate debris would be formed inside the hole and ejected intermittently.

4. Conclusion

We have developed the high-speed laser stroboscopic videography technique to visualize laser-induced processes in microsecond time resolution. Three examples of such visualization are presented.

Laser peening under water was visualized through HSLSV in photoelastic imaging mode and we clearly showed that the secondary shocks and stress is generated when the laser-induced bubble collapses. The magnitude of the second stress is approximately 30 % of the first one.

Dynamics of laser-induced cavitation bubble in liquid were studied through HSLSV in shadowgraph and effects of viscosity of the liquid media were studied. Center position of the bubble moved stepwise to downward when the bubble collapsed while remains the same position during its expansion and shrinkage.

Effects of multiple laser irradiations were visualized in situ in femtosecond laser drilling on WC. HSLSV is capable to visualize the dynamics of laser ablation induced by each single pulse from continuously irradiated 1 kHz laser pulses. Ejection of particulates from the drilled hole occurred intermittently and we could analyze this phenomenon statistically.

The HSLSP technique, in which a high-speed video camera is combined with high-repetition rate short pulse laser, is a quite versatile and powerful tool in dynamical studies of fast phenomena.

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